ERDC/CRREL TR-09-14

Cold Regions Research and Engineering Laboratory

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Monitoring of Streambank Stabilization and River Restoration Structures on Ice-Affected Rivers in Northern Vermont

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Final report

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Ice-Affected Structures Work Unit:

Abstract: Modern river restoration and streambank stabilization designs are taking more natural approaches. Examples include vanes and weirs constructed of rocks or logs that encourage bank sedimentation and direct flow toward the channel center, also rock riffles and weirs to control grade. Successful projects help control bed and bank erosion, re-connect floodplains, increase flow diversity and improve habitat for fish and wildlife. To date, the design of these increasingly popular structures has been largely empirical and little is known about their performance on rivers with ice. In addition to the uncertainty of the structures' survival in ice, little is known about their effects on river ice processes. Recent research at CRREL has developed ice-related design guidance for these structures. This effort included performance monitoring of streambank stabilization and river restoration projects on ice-affected rivers in northern Vermont over the three-year period from 2005 to 2008. Results and findings are presented in this report.

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Preface

This technical report was prepared by Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Group, RS/GIS and Water Resources Branch, US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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This report was prepared under the general supervision of Timothy Pangburn, PE, Chief, RS/GIS and Water Resources Branch; Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this work was performed, Colonel Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters

1 Introduction

River engineers and designers are turning towards more aesthetic and environmentally-friendly streambank stabilization (SS) and river restoration (RR) methods. These increasingly popular structures are built from natural materials such as stone and logs, often accompanied by plantings to stabilize riparian soils. Structure types include rock of log vanes, cross vanes, rock weirs and U-drops (NRCS, 2008, Rosgen, 2001). Depending on the desired objectives, these structures, alone or in combinations are used to:

- Deflect flow towards the channel center and encourage sediment deposition and plant growth along the banks
- Reduce channel or river corridor width
- Improve conveyance of sediment and ice
- Direct and convey flow and sediment through bridge openings
- Increase flow diversity by creating pool-riffle sequences
- Provide grade control, reverse bed incision and reconnect the river channel with floodplains
- Re-establish natural hydrologic processes
- Improve habitat for fish and wildlife
- Improve recreational value of river for canoeing, rafting, whitewater parks, etc.

To date, the design of these increasingly popular SS and RR structures has been largely empirical and little is known about their performance on rivers with ice. In addition to uncertainty about the structures' winter survival, little has been documented about their effects on the ice regime. A critical question is how these in-stream structures affect ice conveyance and ice jamming. Tuthill (2008) presents preliminary design guidance for in-stream structures on ice-affected rivers and Vuyovich et al. (2009) used physical and numerical models to develop more theoretical design approaches. This technical report summarizes observations of river restoration and streambank stabilization structures on selected ice-affected rivers in Vermont during the winters of 2005-2008.

2 Background

<u>Popular types of RR and SS structures and their purposes</u>

Vanes

Vanes constructed of rocks or logs extend out from one bank to direct flow toward the channel center. Vanes are typically angled 20 to 30 degrees upstream from the banks and key into the channel sides at the bankfull elevation. Popular designs typically extend out a maximum of 1/3 of the channel width where the vane merges with the thalweg elevation. A successfully designed vane serves to deflect flow away from banks and towards the channel center, stabilize eroding banks, encourage deposition and establishment of riparian plants to strengthen streambank soils and resist erosion.

Cross vanes

Cross vanes consist of paired vanes extending out from opposite banks, alone or in series. They serve to stabilize banks, direct flow towards the channel center, dig pools, and improve conveyance, flow diversity and fish habitat. A cross vane may be symmetrical with respect to the channel alignment or asymmetrical, depending on the desired direction of flow.

Porous rock weirs

Porous rock weirs differ from cross vanes in that they are more linear in plan view and are level crested. Their purposes include grade control to prevent head cutting or channel deepening. Series of closely-spaced porous rock weirs can be used to create man-made rapids to provide fish passage around dams. The weirs may extend straight across the channel or take a concave-downstream plan view that concentrates flow towards the channel center. In addition to the uses described above, rock weirs have served as diversion structures on western rivers.

U-Drops

U-drops differ from rock weirs in that, rather than having a level crest, they sag near the channel center, roughly paralleling the cross sectional geometry of the river bed. As their name suggests, the weirs have a down-

stream-facing U-shaped plan view to concentrate flow towards the channel center. U-drops which serve many of the same purposes as cross vanes are a common feature in whitewater parks. In this recreational application, the rocks may be grouted to reduce the risk of snagging boats or swimmers.

Channel blocks

Channel blocks are earthen structures, resembling berms, which prevent flow from entering a river channel. They are used to direct flow into desired channels to reverse braiding and over-widening trends. The blocked-off channels often become wetlands, providing habitat benefits.

3 Objectives

The objective of this study was to monitor the performance of selected RR and SS structures on ice-affected rivers over the winter seasons of 2005 to 2008. Important tasks were to:

1. Document effects of the structures on ice formation and ice breakup processes,
2. Identify damages to structures as the result of ice, and
3. Note trends or changes in sediment transport and river morphology as a result of the structures.

Where possible, the overall effectiveness of the structures was assessed in terms of how well they achieved their design purposes. The study also documented unintended outcomes and tried to determine their causes.

4 Projects

Twelve sites were selected for field monitoring on the Winooski, the White, the Mad and the Trout Rivers in northern Vermont. Figure 1 shows project locations. All of these streams have histories of severe ice events. Structure types and their purposes are listed in Table 1. Project sponsors include the Vermont Agency of Natural Resources (VT-ANR), the National Resource Conservation Service (NRCS) and the Vermont Agency of Transportation (V-TRANS). Project design and construction was overseen by these various agencies, with each group having a slightly different perspective and approach.

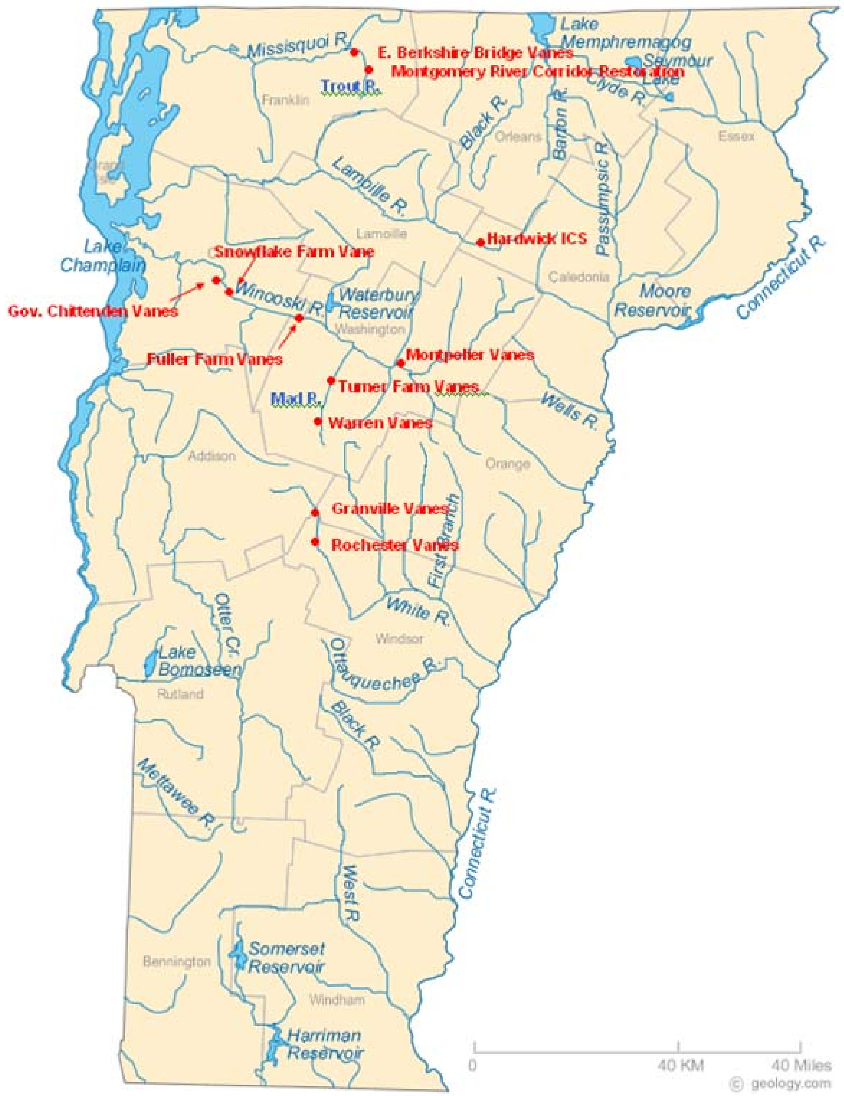

Figure 1. Study site locations

Table 1. Project Sites, Structure Types and Purposes

River	Site	Structure Type	Purpose	Sponsor	Effect
Winooski	Montpelier High School	4 rock vanes	SS	VT-ANR	+
	Fuller Farm, Bolton	4 rock vanes	SS	NRCS	+
	Snowflake Farm, Richmond	1 rock vane, root wad and stone revetment	SS	NRCS	+
	Gov. Chittenden Rd. Williston	3 rock vanes	SS	VT-ANR	+
Mad	Warren Snow Making Ponds	rock vanes, cross vanes, rock weirs	SS, RCR, GC,	VT-ANR	+
	Waitsfield	rock vanes, wooden posts	SS, IC	VT-ANR	0
	Fuller Farm	3 short rock vanes			0
Trout	Below Montgomery Village	Rock vanes, log vanes, cross vanes, channel cutoffs	SS, RCR	VT-ANR	-
	u/s East Berkshire Bridge	Rock weirs, vanes, cross vanes, channel cutoffs	SS, RCR, GC	V-TRANS	+
White	d/s Granville	2 rock vanes, 4 cross vanes	SS, IC	VT-ANR	+
	u/s Rochester	vanes, cross vanes, wooden posts, berm	SS, IC	VT-ANR	+

SS = streambank stabilization, CG = grade control, RCR = river corridor restoration, IC = ice control

VT-ANR=VT Agency of Natural Resources, NRCS=National Resources Conservation Service, V-TRANS = VT Agency of Transportation

In this study, multi-structure projects were favored over single structure sites, as it was hoped that the ice-structure interaction would be easier to discern. While all projects included rock vanes for streambank stabilization, five included additional structure types (cross vanes and rock weirs) for purposes of grade control, sediment conveyance and river corridor restoration. Two of the VT-ANR vane projects included elements of ice control (rows of wooden posts to retain breakup ice within the river channel).

5 Environmental and Physical Site Data

Environmental Data

Environmental data collected for the monitoring period included daily air temperature, precipitation and river discharge. Annual mean flows and the 1.5 year recurrence interval discharge ($Q_{1.5}$) were calculated. $Q_{1.5}$ was assumed to approximate the bank full discharge, also described as the channel forming discharge. Many consider bank full discharge and stage to be important parameters in the design of river restoration projects (NRCS, 2008, Rosgen, 2001).

Figure 2 plots daily average air temperature, precipitation and net accumulated freezing degree days (AFDD) for the winters of 2005 to 2008. Accumulated freezing degree days (AFDD) are a running sum of the freezing degree days which are calculated as 32˚F – the daily average air temperature. To calculate net AFDD, the AFDD curve is reset to zero once it takes on a consistently positive slope (USACE, 2006).

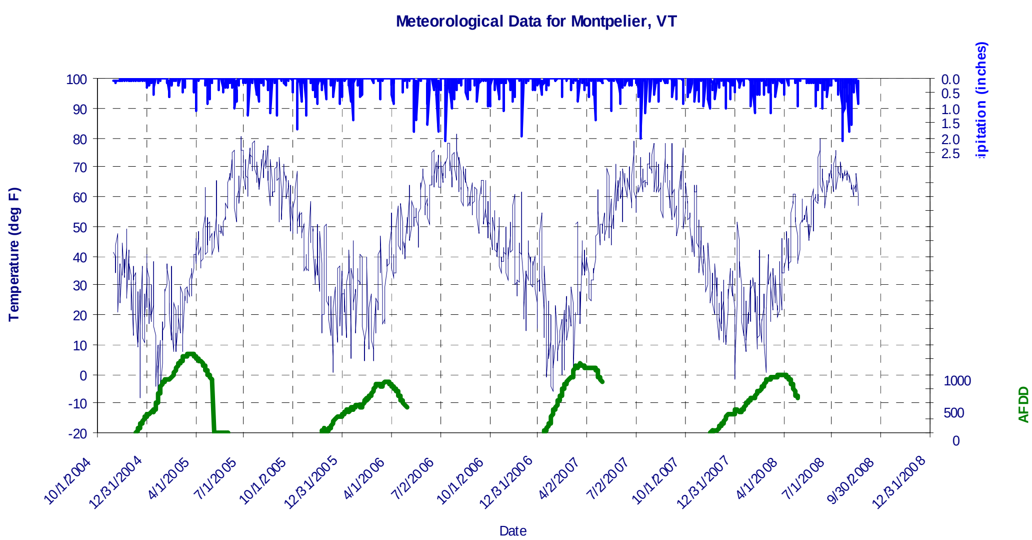

Figure 2. Daily average air temperature, accumulated freezing degree days and precipitation for water years 2005-2008, at Montpelier, VT.

Figure 3 plots the maximum net AFDD at Montpelier, VT for the 1950-2009 periods. Maximum net AFDD are a good indicator of ice production in regional rivers. The average of the maximum AFDD for the 2005-2008 study period is 1094, significantly less than the 1950-2009 average value

of 1380, even after the long term decreasing trend in maximum AFDD is taken into account. This indicates that the winters of the four-year study period were relatively mild in the long term in context of air temperature.

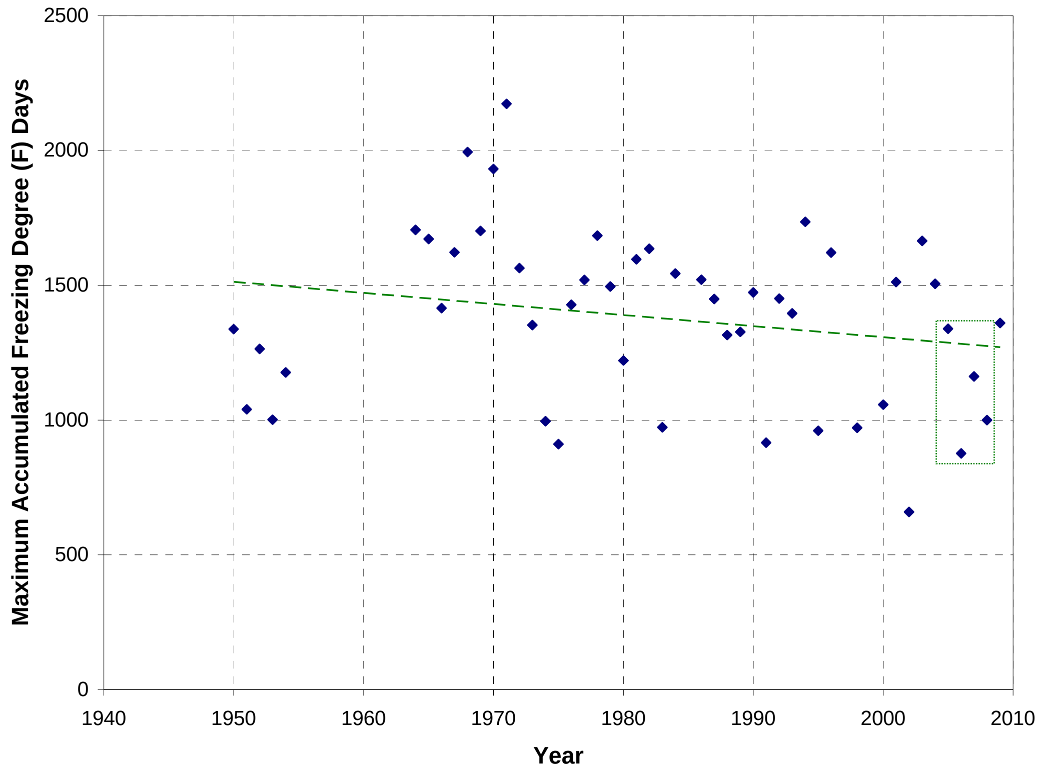

Figure 3. Maximum net accumulated freezing degree days at Montpelier, VT 1950-2009.

Figure 4 plots daily average discharge for water years 2005-2008 on three of the rivers hosting the projects: the Winooski, the White, and the Mad. The Mississquoi is included since it is geographically close to its ungaged tributary, the Trout River, where two of the projects are located. The bankfull discharges listed in Table 2 are estimated from the discharge vs. drainage area relationships shown in Figure 5.

Table 2. Site Characteristics

River	Site	Drainage Area (mi²)	Valley Bottom Slope	Bank-full Width (ft)	Bank-full Depth (ft)	Bankfull Discharge $Q_{1.5}$ (cfs)	Mean Discharge (cfs)	Bed Material &D_{50}	Sinuosity
Winooski	Montpelier High School	397	0.001	180	12	6080	606	sand	1.2
	Fuller Farm, Bolton	715	0.001	250*	12	12,500	1100	sand-gravel	1.0
	Snowflake Farm, Rich-mond	950	0.000 6	250	15	17,000	1400	sand-gravel	1.6
	Gov. Chitten-den Rd. Willis-ton	990	0.000 5	300	15	18,000	1600	silt-sand	1.7
Mad	Warren Snow Making Ponds	100	0.003	150	6	1200	100	gravel	1.3
	Waitsfield	250	0.003	200	8	2800	250	gravel-cobble	1.4
	Turner Farm	300	0.003	180	8	3900	300	cobble	1.3
Trout	Below Mont-gomery Vil-lage	44	0.002	80	3.3	1700	~125	gravel (0.5 in)	1.3
	u/s East Berk-shire Bridge	86	0.003	100	8	3200	~180	gravel	1.3
White	d/s Granville	~75	0.007	60	4	~1500	~200	gravel-cobble	1.2
	u/s Rochester	~100	0.0015	100	8	~3000	~250	gravel-cobble	1.2

* vanes in 70-ft-wide side channel

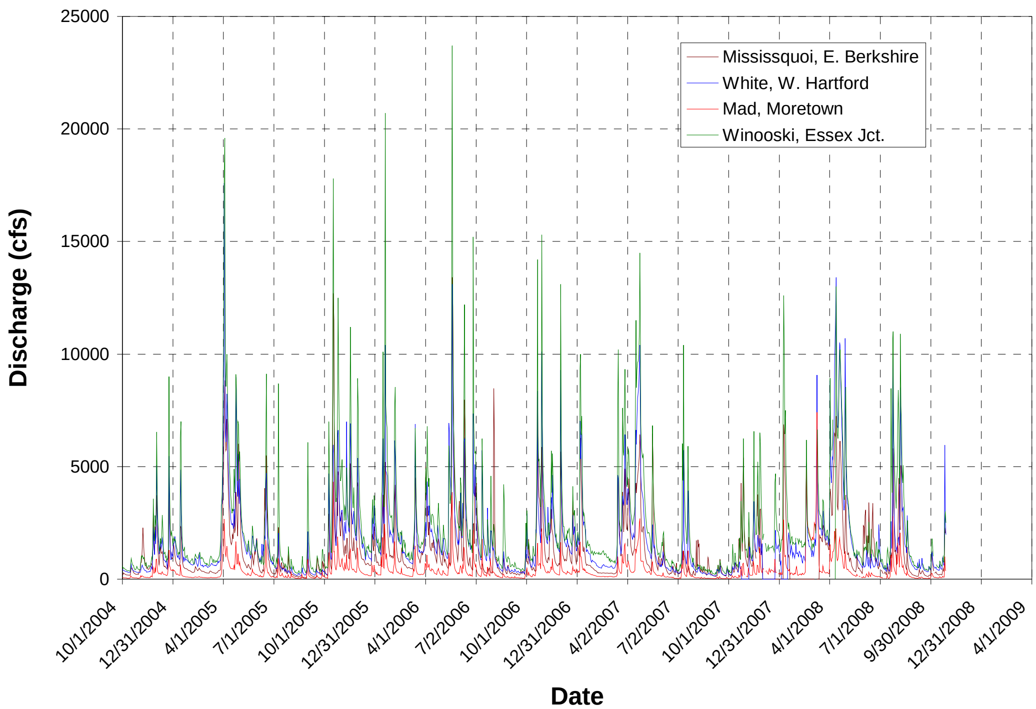

Figure 4. Daily average discharge for selected Vermont Rivers , water years 2005-2008.

Figures 6-9 show the meteorological and river discharge data for the individual winters of 2005, 2006, 2007 and 2008. These hydro-meteorological data indicate the nature of ice formation and breakup for the individual winters.

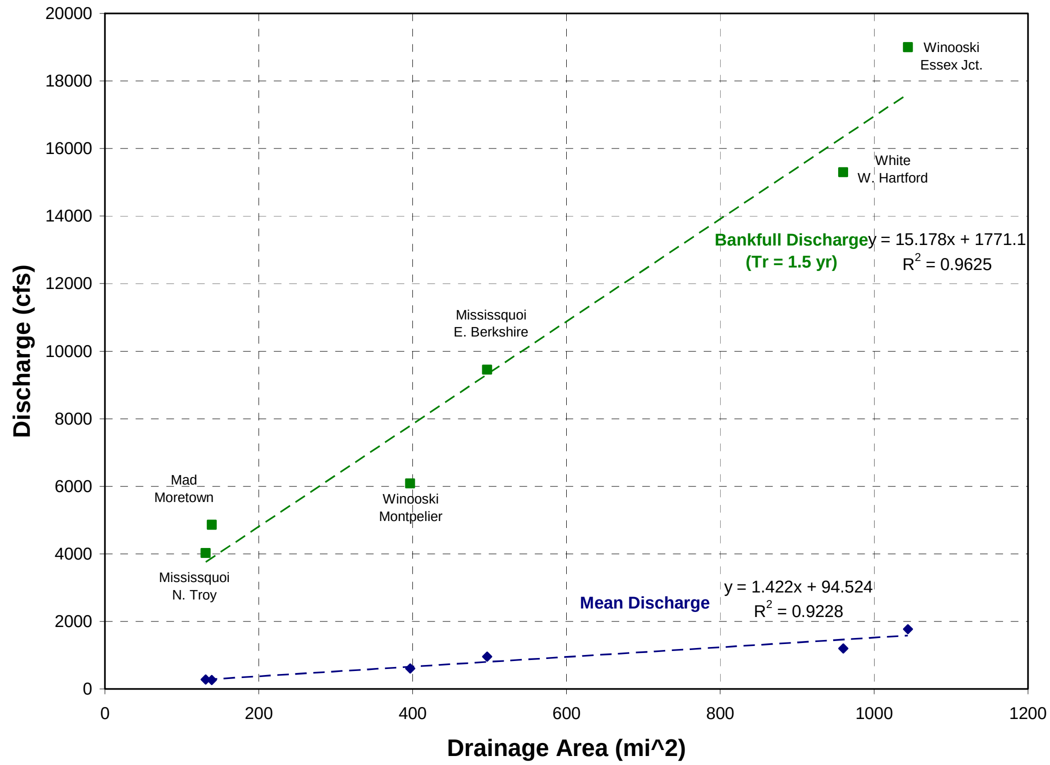

Figure 5. Discharge vs. drainage area for selected Vermont River

The winter of 2005 was average in coldness but experienced two thaw events on 3 and 24 January that broke up much of the ice on the rivers (Figure 6). Typically, ice covers begin to establish on Vermont rivers once the AFDD have reached about 300, and in the absence of major thaws or mid-winter breakups, thermally-grown ice covers can reach thicknesses as great as 18 inches. Because of the two mid-winter breakups, the 2005 late winter ice cover was below average in both thickness and extent. The typical breakup period of mid-March to early April was characterized by gradual warming and steady flows leading to a thermal meltout rather than a dynamic ice breakup. From the point of view of monitoring the ice resistance of the in-stream structures, the below-average ice cover and mild late-season breakup of 2005 were unfortunate.

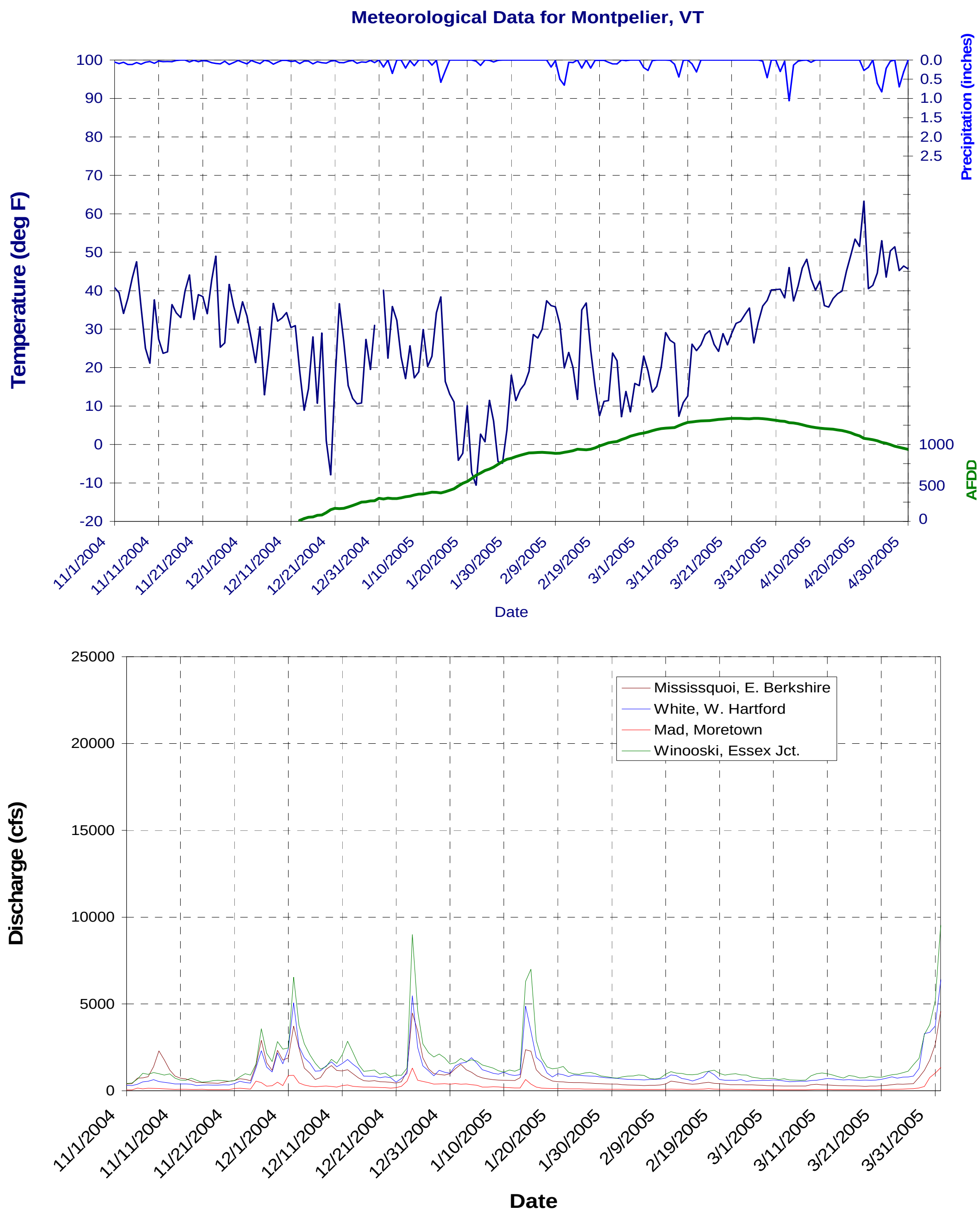

Figure 6. Daily discharge and meteorological data for the winter of 2005.

The winter of 2006 was the mildest of the study period. In addition to the below-average early winter ice production, a major thaw at the end of January broke up the relatively thin ice cover. The lack of any extended cold periods after this limited the extent and thickness of the ice that was able to form during the remainder of the winter (Figure 7). The 2006 breakup, with low ice volume and minor flow increases, posed little potential threat to the in-steam structures.

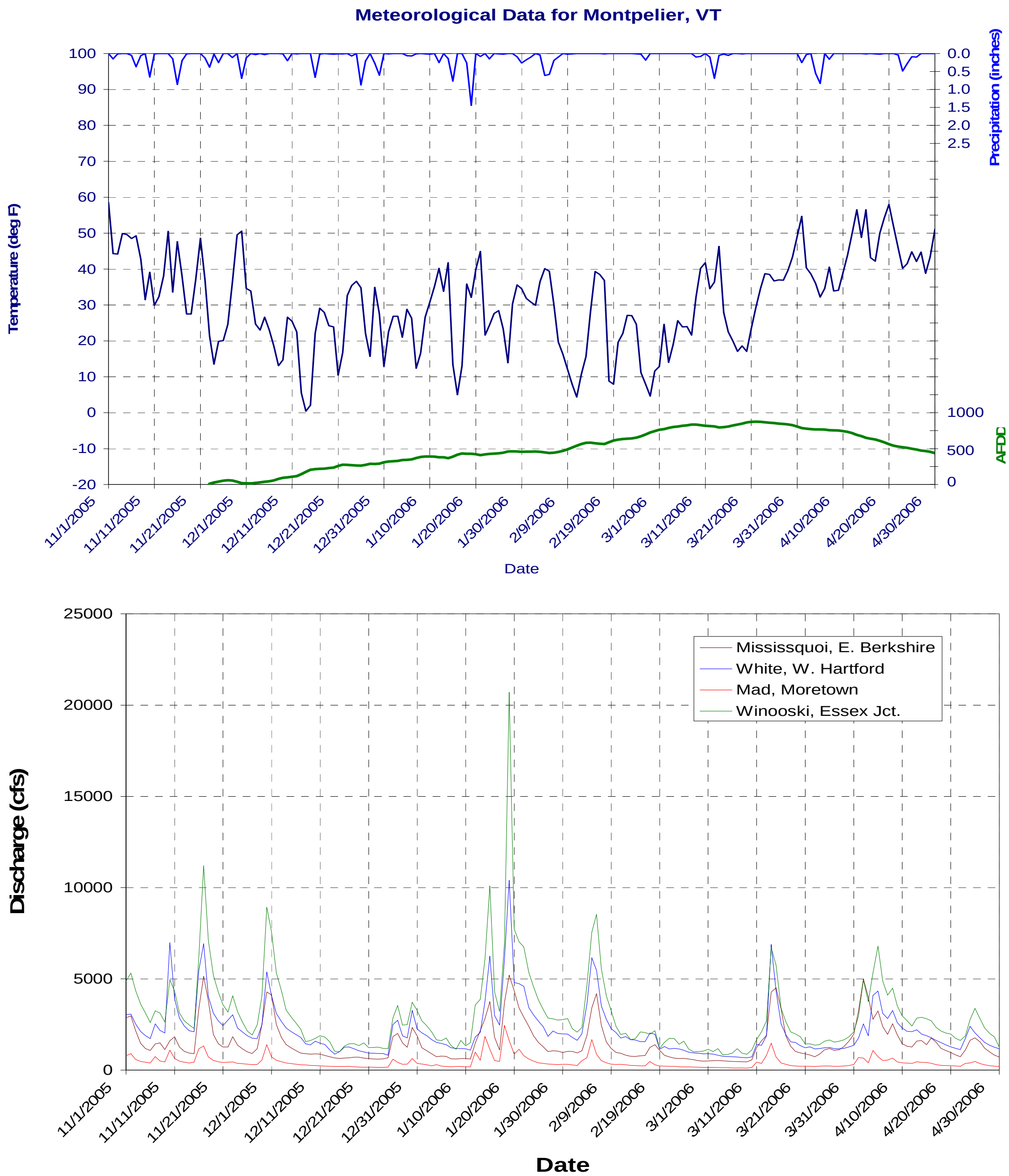

Figure 7. Daily discharge and meteorological data for the winter of 2006.

November and December of 2006 were unusually wet and warm, producing very high flows on regional rivers (Figure. 8). Though late to start, ice formation in the latter half of January was rapid due to the abundant open water area for heat transfer, high flows and extreme cold. This combination produced thick accumulations of frazil and freezeup ice jams at unusual locations. A major concern was that the freezeup ice jams would remain in place to cause breakup ice jams and flooding. The thaw and hydrograph peaks of the 24 March 2007 thaw almost triggered serious breakup ice runs and jams, but an abrupt return to colder weather caused

most ice covers to remain in place and slowly melt out in the two weeks that followed. Again, no dynamic ice runs occurred to test the in-stream structures.

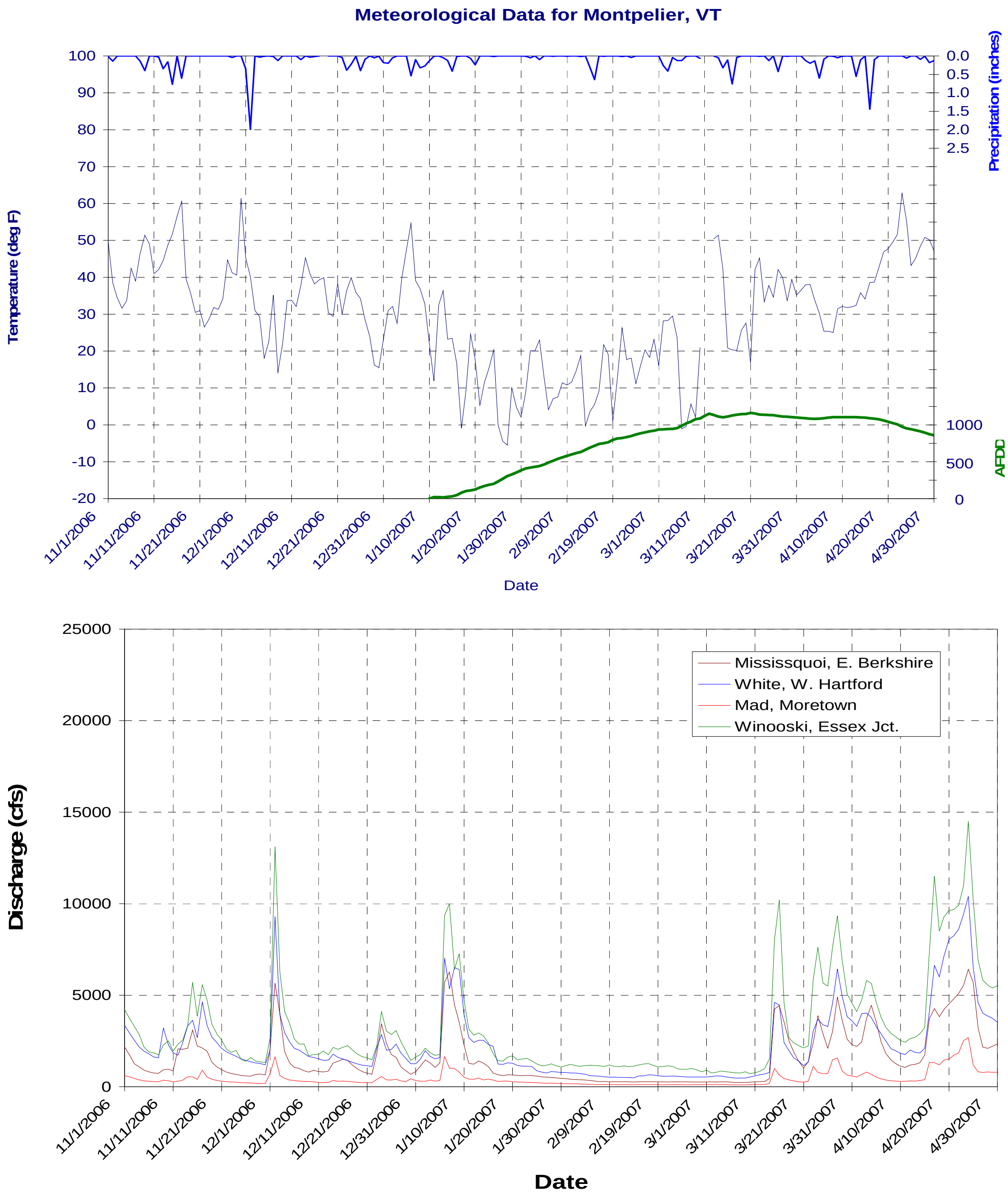

Figure 8. Daily discharge and meteorological data for the winter of 2007.

The winter of 2008 followed a similar pattern to 2006, being nearly as mild with a mid-winter breakup in late January that cleared out the ice and limited the late season ice volume. Again, late winter runoff was insufficient in magnitude to cause dynamic breakups to provide a significant test the ice resistance of the structures (Figure 9).

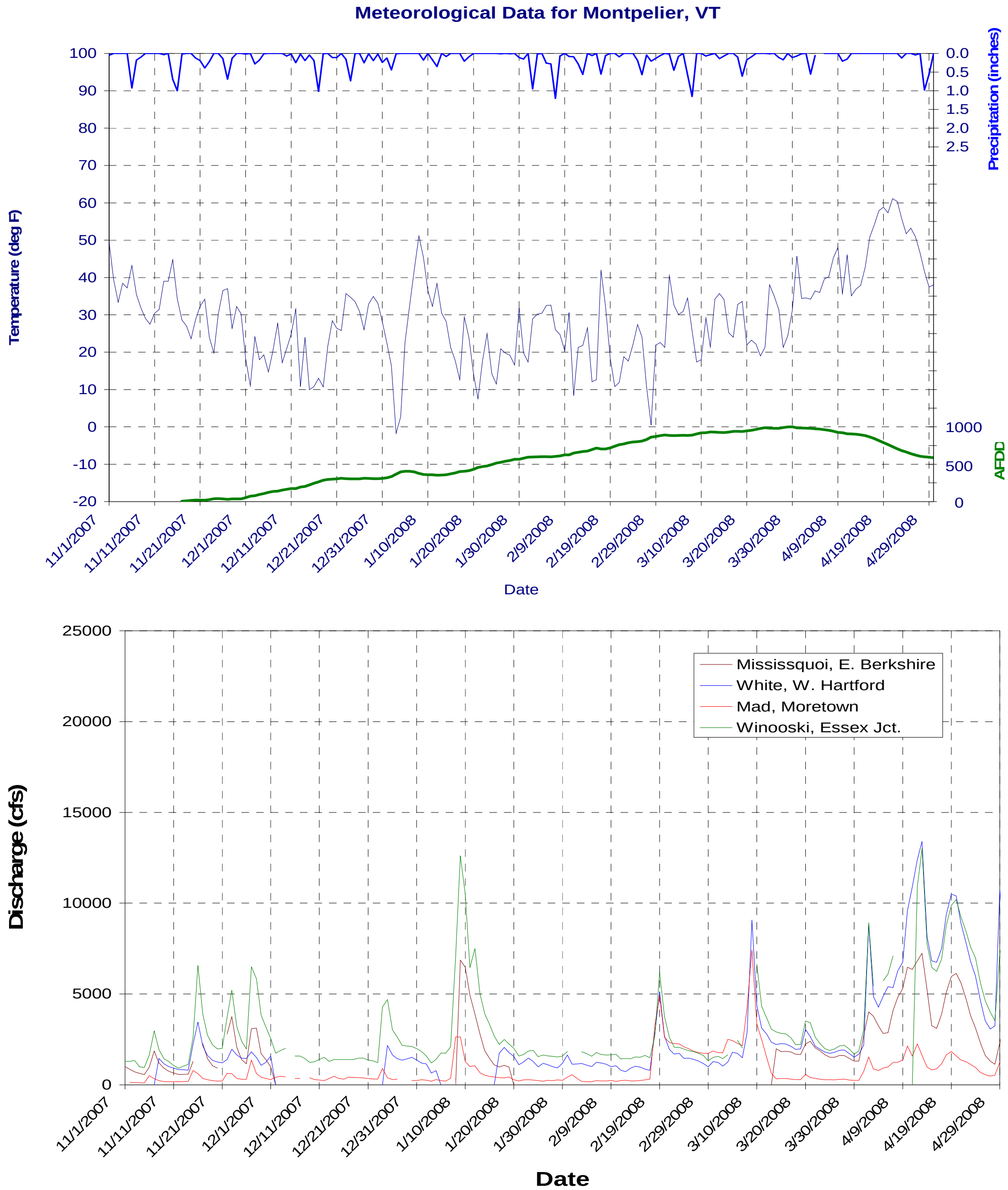

Figure 9. Daily discharge and meteorological data for the winter of 2008.

Site Data

Physical characteristics of the project reaches, summarized in Table 2, include drainage area, average bed slope and bankfull width, depth and discharge. Also tabulated are mean annual discharge, bed material and channel sinuosity. The projects represent a fairly wide range of river size and type. With the exception of a few flood control reservoirs on tributaries of the Winooski, the project rivers are unregulated and relatively unaltered by human activities. Drainage areas range from 990

mi^2 on the lower Winooski to 44 mi^2 on the upper Trout Rivers. Channel slopes range from 0.007 on the upper White River to 0.0006 on the lower Winooski with a corresponding increase in bankfull discharge from 1500 cfs to 18,000 cfs. Bed material ranges in size from cobbles and gravel in the steeper upstream reaches to silty sand at the lower gradient downstream sites.

Data were gathered in the form of observations and photographs from both the ground and by airplane on nine different days over three winter seasons (Table 3). The bulk of the data were collected during the winter of 2005-2006.

Table 3. Site Visit Dates

River	Site	11/2/05	11/28/05	12/14/05	12/21/05	1/4/06	1/10/06	3/8/06	3/21/07	1/31/08
Winooski	Montpelier High School		G	A	A			A	A	A
	Fuller Farm, Bolton	G, A	G		A	A	G	A		A
	Snowflake Farm, Richmond		G		A	A				A
	Gov. Chittenden Rd. Williston	G, A			A	A		A		A
Mad	Warren Snow Making Ponds	G, A			A	A	G	A		
	Waitsfield	G, A			A	A	G	A		
	Turner Farm	G, A			A	A	G	A		
Trout	Below Montgomery Village		G		A	A		A	A	A
	u/s East Berkshire Bridge		G		A	A		A	A	A
White	d/s Granville	A			A		G			
	u/s Rochester	A			A		G	A		

6 Project Descriptions

Winooski River, Montpelier: Rock Vanes

A series of five rock vanes were constructed in the Cemetery Bend reach of the Winooski River to stabilize the banks along the Montpelier High School playing fields (Figure 10). The vanes, which are spaced about one channel width apart, form about a 25˚ angle with the upstream bank and protrude into the river about 25 ft.

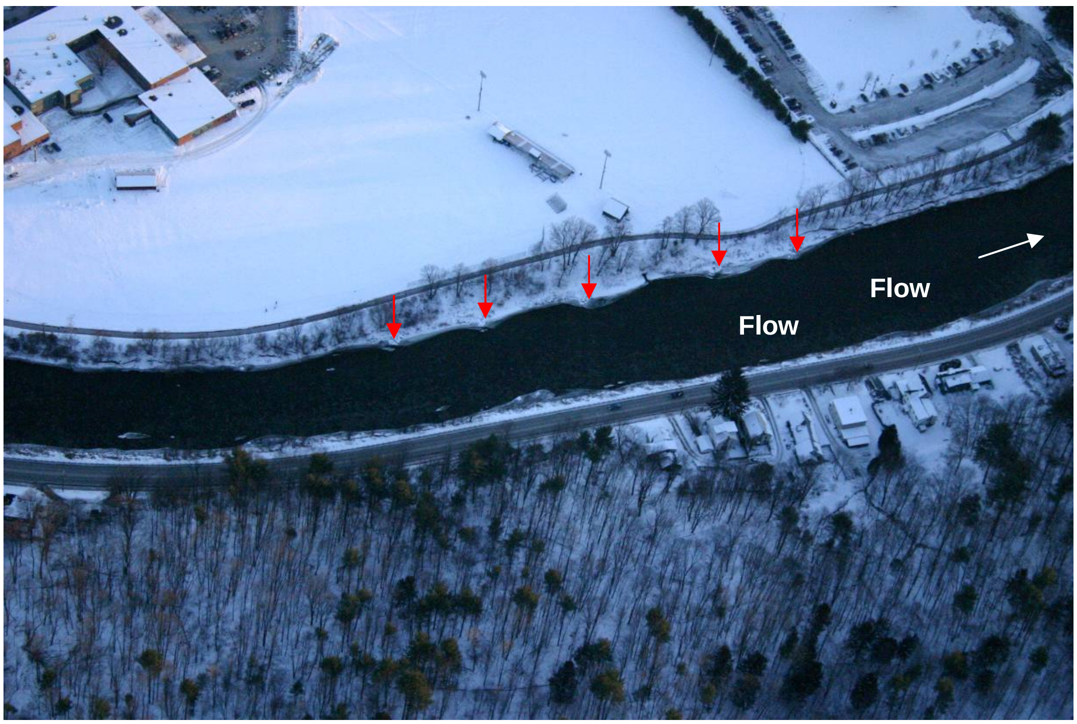

Figure 10. Rock vanes on the Winooski River at Montpelier, VT 12/21/05.

The randomly-placed rocks have an average diameter of about 1.5 ft. and a maximum diameter of about 2 ft. (Figure 11). The vanes tie into a narrow terrace at about half of the total bank height. Although the vane profiles represent only a small portion of the total cross sectional flow area, they effectively deflect flow away from the banks at normal flows and create zones of slower water in between, promoting sedimentation and the formation of stable sheet ice in winter (Figure 12).

Figure 11. Rock vanes on the Winooski River at Montpelier, VT viewed from downstream on 7/6/04.

Figure 12. Rock vanes on the Winooski River at Montpelier, VT. viewed from upstream on 1/10/06.

Cemetery Bend, which lies in a transition zone from steeper to flatter gradient, is an historic ice jam location on the Winooski. The Montpelier ice jam of March 12, 1992 formed about 1000 ft. upstream of the project site. During the course of the day, discharge and stage increased to well above bankfull levels before the jam released en-masse.

Since no major open water floods or dynamic ice runs have occurred at Montpelier since the vanes were built in about 2000, their resistance to an event of this magnitude is unknown. As mentioned in Section 5.1, in January of 2007, an unusual freezeup ice jam formed in this section of the Winooski River as a result of high early winter flows and cold air temperatures. This average 4-ft-thick frazil ice accumulation remained in place until a mid-March thaw occurred that caused great concern by nearly releasing the upstream ice cover on top of the downstream freezeup jam. In the end, the jam and upstream ice melted out slowly without incident.

Because they protrude only a short distance into the channel and tie in to the banks well below the bankfull elevation, it is unlikely that the Montpelier vanes have a significant effect on freezeup or breakup ice processes on the Winooski at Montpelier. The vanes appear to be having a positive effect in terms stabilizing the banks. Assuming that they survive over the long term, the vane structures at Montpelier provide a much lower impact alternative to a traditional stone revetment.

Winooski River, Bolton: Fuller Farm Rock Vanes

Four rock vanes help to stabilize about 800 ft. of bank along fields of the Fuller Farm in Bolton, VT (Figure 13). Designed by the NRCS, these vanes form about a 25˚ angle with the upstream bank. They have a mild upstream and a steep downstream slope to allow the ice to slide up and over, minimizing the potential for rock displacement (Figure 14). The vanes, which cost about $8,000 each to build, are keyed 15 ft. into the top of the bank. They incline downward into the river to intersect the bed elevation about one-third of the way across the channel. About 2,000 live willow stakes, which were planted, appear to be thriving. Sediment has deposited along the shoreline upstream of the vanes while deep scour holes have formed in the channel downstream of the structures. The rocks, which are up to 4 ft. in diameter, were individually placed by a large excavator. The ramp-like form of the vanes provided convenient access for

the construction machinery while minimizing disruption of trees and riparian vegetation.

Figure 13. Rock vanes on the Winooski River, Fuller Farm, Bolton, VT on 11/2/05.

Figure 14. Rock vanes on the Winooski River, Fuller Farm, Bolton, VT viewed from upstream on 11/2/05.

A photo taken during the freezeup period in January 2006 shows border ice forming around the vanes in patterns similar to the observed sedimentation (Figure 15). No dynamic ice breakups have occurred in this section of the Winooski since 2002, when the project was built. From the plan configuration of the channel, it appears that the breakup ice run would probably follow the main channel to the left of the island and not impact the structures directly. Another mitigating factor is the project location, about 3.5 miles downstream of the Bolton Falls Dam, which likely impedes the breakup ice run and lessens potential ice impacts to the structures.

Figure 15. Ice forming around rock vanes on the Winooski River, Fuller Farm, Bolton, VT 1/4/06.

Winooski River, Richmond: Snowflake Farm Rock Vane and Revetment

A large rock vane and stone revetment stabilize the banks at the Snowflake Farm property, about 1 mile downstream of Richmond Village (Figure 16). This NRCS vane, shown in Figures 17 and 18, is similar to but larger than the Bolton Farm vanes. Constructed of 4’×3’×2’ quarried stone, the 30-ft-long structure is keyed 20 ft. into the top of the wooded bank and ramps gradually into the river forming a 15° angle with the upstream bank. The structure is built at the entrance to a flood chute where, during high flow events, water escapes the main channel to shortcut the wide bend downstream. Downstream of the vane, the edge of a field has been

armored with about 800 ft. of riprap, reinforced with buried root wads spaced about 50-ft-apart. It appears that the vane serves in part as a flow deflector to protect the upstream end of the revetment. The total cost of this NRCS project was $60,000, $15,000 of which was for the vane.

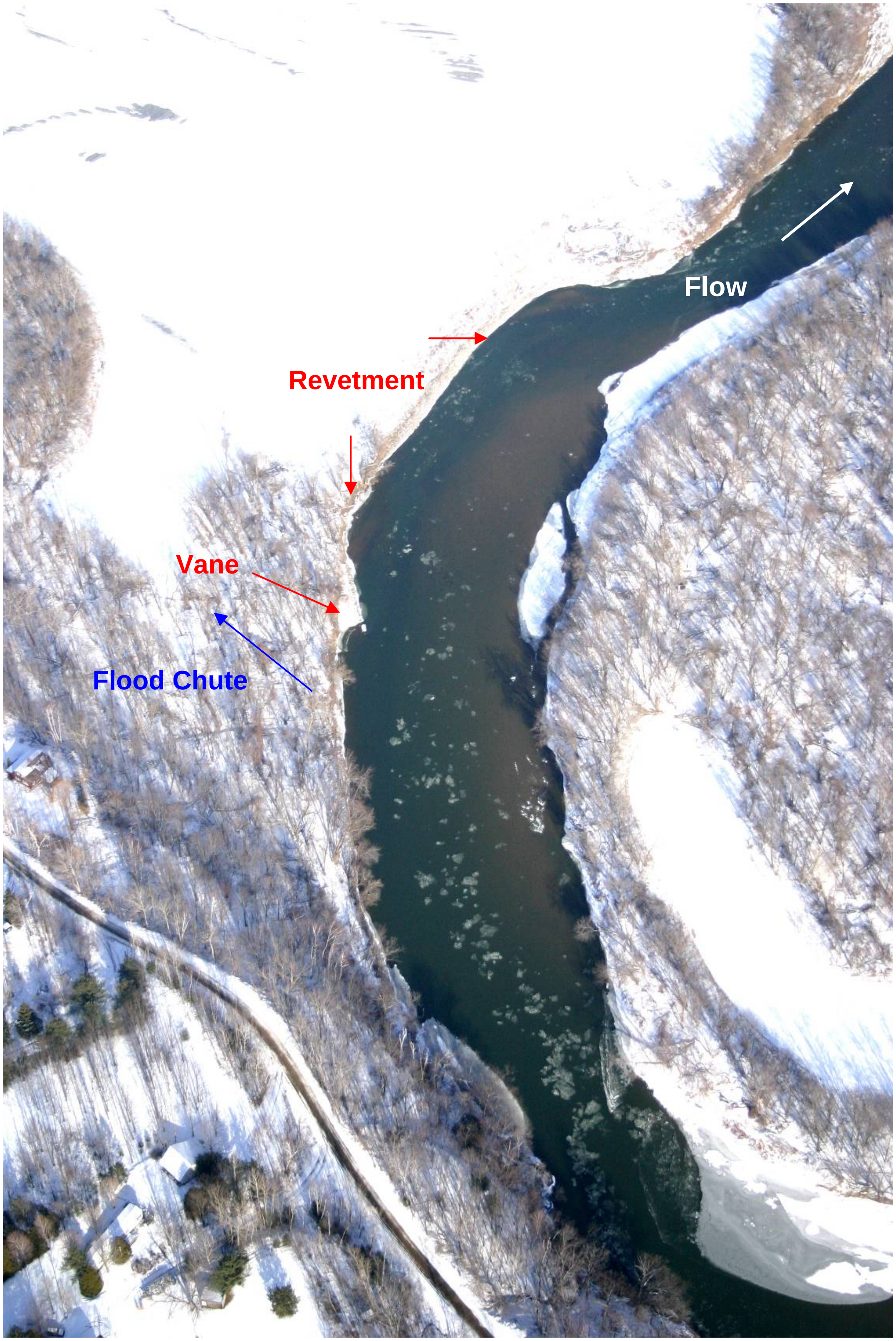

Figure 16. Frazil pans drifting past vane and revetment at the Snowflake Farm property downstream of Richmond, VT, 1/31/08.

Figure 17. Vane and revetment at Snowflake Farm viewed from upstream on 11/28/05.

The trees in this area have been heavily scarred by ice to heights 5 ft. above the floodplain elevation (Figure 18) indicating heavy ice action in the past. This is not surprising since the 10 mile section of river from the Bolton Dam to Richmond Village is relatively straight with few features to impede the movement of breakup ice. Just downstream, the Snowflake Farm property lies in a transition zone into a wider valley with increased sinuosity and reduced slope. In light of these factors, one would expect heavy ice impacts at the Snowflake Farm site. As a result of the relatively mild environmental conditions of the recent series of winters, the project has not been tested by a severe ice event since its construction in 2003.

Figure 18. Entrance to flood chute at Snowflake Farm 11/28/05. Note tree scars due to ice.

Winooski River, Williston: Gov. Chittenden Rd. Rock Vanes

Three rock vanes deflect flow away from the outside of a bend along the Gov. Chittenden Rd. in Williston (Figures 19 and 20). The vanes, built in 2001, provided an economical and more aesthetic alternative to toe stone to prevent undermining of the adjacent roadway embankment. The vane structures tie into the bank at the bankfull elevation and extend about 1/3 of the way across the channel, merging with the existing river bed elevation at their tips. They form an upstream angle with the bank of about 27°. Upslope of the vanes, 500 ft. of sheet piling with under-drains stabilize the road embankment. The VT-ANR designed and oversaw construction of the project, which cost about $0.5 million. The project has strong local support, particularly among anglers who believe the vanes improve fish habitat.

At the time of the 2 November 2005 visit, the Winooski discharge was up and the vanes were visibly diverting flow away from the banks, towards the channel center. On a 28 November 2005 visit, the water was lower, exposing randomly-placed riprap with an average diameter of about 12 inches (Figure 19).

Figure 19. Cross vanes on the Winooski River along Gov. Chittenden Rd. viewed from upstream on 11/28/05

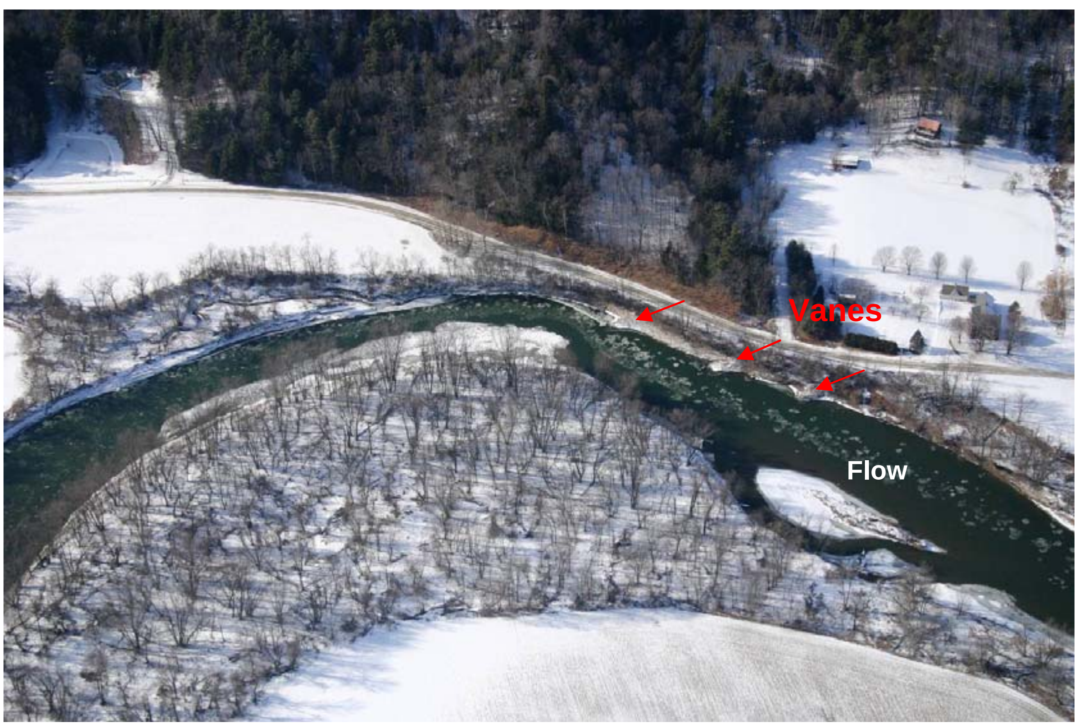

Figure 20. Drifting frazil ice and shore ice forming around vanes and on the Winooski, R. at Gov. Chittenden Rd. vanes, 1/31/08.

These vanes appear more symmetrical in cross section than the upstream NRCS-designed projects on the Winooski. Photos from a 31 January 2008

flyover show the vanes effectively deflecting drifting frazil pans towards the channel center (Figure 20). Judging from the upstream channel configuration, abundant tree scarring, and anecdotal accounts, the Gov. Chittenden site can experience significant ice action during the breakup period (Figure 21). No major ice events have occurred on this section of the Winooski in the eight years since the vanes were built however.

Figure 21. Heavy tree scarring by ice along Winooski, R. at Gov. Chittenden Rd. vanes, 11/2/05.

Mad River, Warren: Rock Weir, Vanes and Cross vanes

This project on the Mad River, two miles below Warren, includes two cross vanes, a vane and two revetments that stabilize banks and improve conveyance around a man-made snowmaking water storage pond (Figures 22-24). At the head of the reach, a stone revetment armors the bank along the pond. Below the revetment, a gated wooden weir serves the dual purposes of grade control and pond filling. Downstream, two cross vanes and a single vane encourage sediment deposition along the left side of the channel and concentrate flow towards the channel center.

Figure 22. Channel restoration structures on the upper Mad River at the Warren snowmaking ponds. 11/2/05

Figure 23. Partial ice cover on the upper Mad River at the Warren snowmaking ponds. 12/21/05.

Below the vane, the channel narrows and bends to the left along a stone revetment. After two ledge drops, the stream bends sharply back to the right. It is likely that these knick points and sharp bends, in addition to controlling grade, delay passage of the breakup ice run through the project reach. In the past, the river has gone out of bank and into the pond in the vicinity of the wooden weir.

An aerial view on 10 January 2006 shows a continuous open lead along the path of fastest current. The lead narrows at the structures where border ice has formed around the vanes (Figure 23). It appears that the river is still aggrading in the vicinity of the upstream cross vane, as the rocks forming the left hand vane (facing downstream) are now nearly buried in gravel (Figure 24).

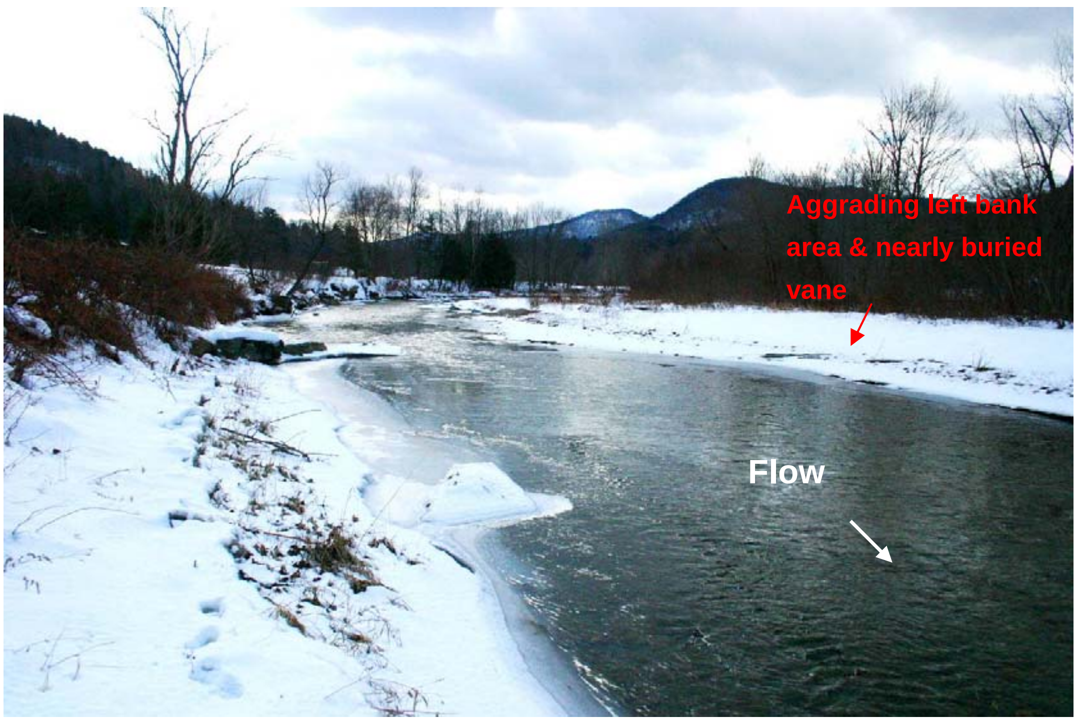

Figure 24. Mad River near Warren, upper cross vane viewed from downstream on 1/10/06. Note aggradation on the left bank (looking downstream) has nearly buried the vane.

Based on the three winters of observation, this section of the Mad River does not appear to experience dynamic breakup ice runs. No evidence was found of ice jam tree scars, as observed on the Winooski. This lack of ice jam evidence could be due to the limited upstream channel length and area which restricts the capability to form and contribute ice to the breakup ice run.

Mad River, Waitsfield: Rock Vanes, Posts

Several small rock vanes were constructed at least ten years ago stabilize the left bank of the Mad River immediately below Waitsfield Village (Figure 25). The vanes tie into the bank well below the bankfull elevation and do not extend very far into the channel.

Figure 25. Mad River at Waitsfield: Site of two small rock vanes and ice retention posts. 11/2/05.

A double row of wooden posts lines the top of the bank to prevent debris and breakup ice from escaping into the adjacent field (Figure 26). At this point, the posts have started to rot and would probably not withstand an extreme ice event. On a 2 January 2005 visit, the rock vanes did not appear to be having much effect in terms of deflecting flow away from the shore. Several hundred yards downstream in a tight bend to the left, the river channel cuts into a clay bank, a large portion of which has slid into the river. This sharp bend is a possible breakup ice jam location. It could be that erosion and ice action since construction have diminished the original size of the rock vanes and decreased their effectiveness.

Figure 26. Mad River at Waitsfield: Ice retention posts 11/2/05.

Mad River, Waitsfield: Turner Farm Spur Dikes

Three rock vanes or spur dikes were built along the left bank of the Mad River upstream of the Turner Farm near a location where, on past occasions including a 1998 flood, the river has gone out of bank to erode a large portion of an adjacent field (Figure 27). The designer's intention may have been to stabilize the bank in response to the 1998 flood, but because the vanes do not extend far enough out into the channel, or because they have been extensively damaged by ice or erosion, they did not appear to have much effect on flow patterns during an 2 November 2005 visit to the site (Figure 14). Tree scars in the vicinity of the project suggest that dynamic ice breakups occur at this site. It is unknown whether any of the overbank flow events and field erosion was ice jam related.

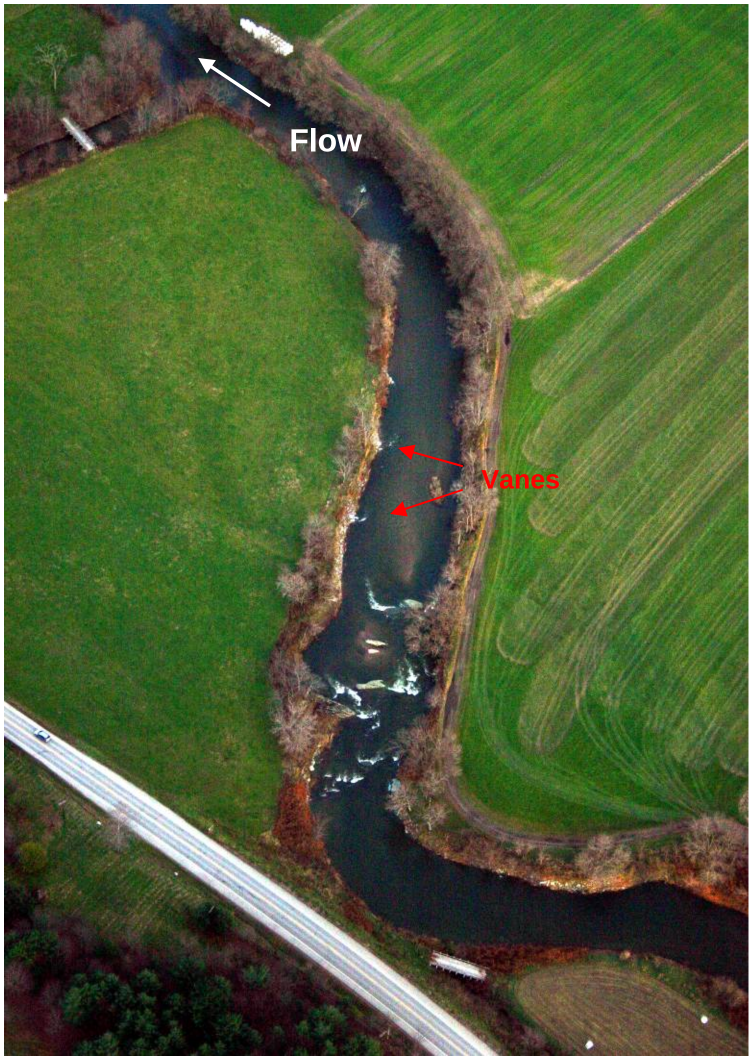

Figure 27. Mad River. Turner Farm vanes 11/2/05

Trout River, Montgomery Center: Rock Vanes, Log Vanes, Cross vanes, Berms and Channel Cutoffs

This river corridor restoration project, completed in 2000, is located about one mile downstream of the village of Montgomery Center in a zone where the Trout River transitions from steep mountain valleys into a ¼-mile wide, relatively flat valley bottom. As a result, much coarse bedload deposits in the project area causing high rates of bank erosion, braiding and channel widening. Though the predominant land use in the project area is now agricultural, and system wide-sediment fluxes appear fairly stable, the basin may still be re-adjusting to the effects of past deforestation, particularly during extreme flow events. A major flood in

1997 exacerbated the deposition, braiding and bank erosion in the project area, prompting a major effort to restore the channel to a stable width, depth, slope and meander plan. This project, the largest of its kind in northern New England, was accomplished through the collective efforts of local volunteers, state and federal agencies. VT-DEC (2001) provides an overview of the project objectives as well as design approach and early performance.

Through the use of vanes, berms and channel blocks, the braided portion of the river was trained into a single channel leading away from the eroding Route 118 embankment and connecting with a former meander (Figures. 28 and 29). Restored channel characteristics (width, depth, slope and sinuosity) were determined through comparison to stable reference reaches located downstream of the project and sediment transport estimates based on channel slope.

Figure 28. Mad River. Turner Farm upstream vane 11/2/05.

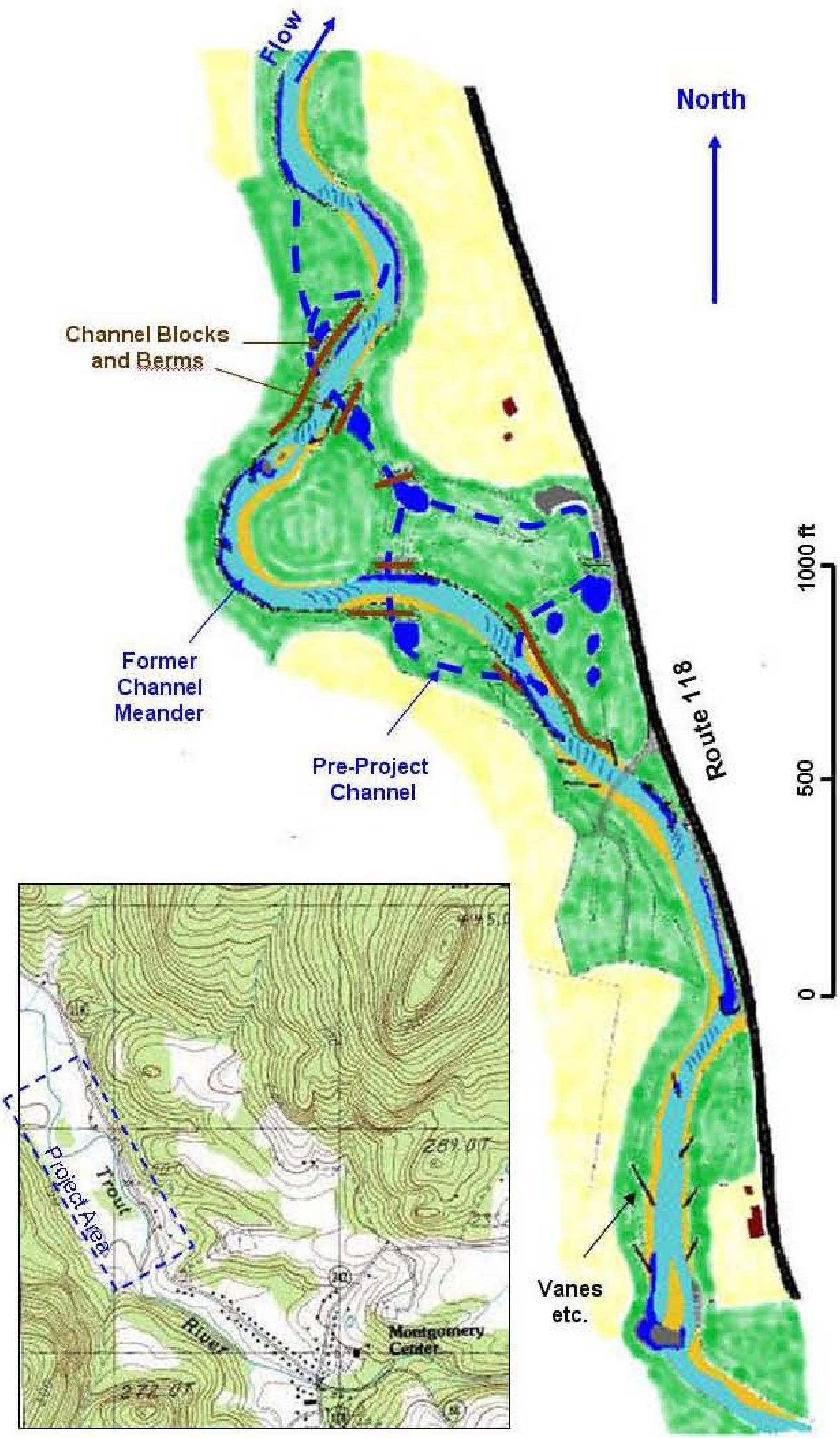

Figure 29. Map of restored Trout River channel below Montgomery Center, VT. Dashed blue lines show path of braided pre-project channel. Sketch map from VT-DEC (2001).

The project performed successfully for its first five years until an extreme flow event, on 17 October 2005, deposited a large volume of coarse bed material in the meander, causing a major avulsion into the blocked-off former channels to the right (Figures 30-34).

Figure 30. Cross vanes stabilize banks of channel diverging from Rt. 118 on the Trout River 11/28/05

Figure 31. Gravel deposits in meander during October 2005 flood caused major avulsion to the right into former channel area. Photo taken 11/28/05.

Figure 32. Recent air photo of Trout River restoration project below Montgomery Center. Deposition of coarse material in large meander during October 2005 flood caused a channel avulsion into the former channel area to the right.

Figure 33. Trout River looking downstream at eroding bank on 11/28/09.

Figure 34. Trout River looking downstream at braided channels on 11/28/09.

Being fairly far upstream in the watershed, it is not clear what role breakup ice events play in this section of the Trout River. Figure 35 shows a partial ice cover on the project reach on January 4, 2006. No evidence of

past ice tree scars was found within the project area, even in the upstream portion where a straight section of river impacts the Route 118 embankment at a sharp angle. It appears that the geomorphologic processes at this site far outweigh ice action in terms of destructive potential.

Figure 35. Ice forming on the Trout River restoration project below Montgomery Center on 1/4/06.

Trout River East Berkshire Bridge: Rock Weirs, Vanes, Cross Vanes, Berms and Channel Blocks

This river restoration project, completed in 2004, consists of a series of vanes, cross vanes, U-drops and rock riffles to control grade and direct the lower Trout River through a new bridge opening on VT Route 118 (Figures 36 and 37). Design and construction were overseen by the Vermont Department of Transportation (V-Trans). Root wads protrude from reshaped banks near the rock structures, and tree revetments were also installed at a few locations. Two rock riffles are located 300 and 1000ft. upstream of the bridge, consisting of four rows of large rocks. These help control grade, along with a series of U-drops and rock weirs. To the right of the restored channel, several channel blocks cut off a former flood chute.

Figure 36. Trout River looking downstream at a U-drop and rock riffles at the East Berkshire Bridge restoration project on 11/28/05.

Figure 37. Trout River looking upstream at the East Berkshire Bridge restoration project on 12/3/08.

The structures were overtopped and the flood chute was accessed during the same high flow event that damaged the upstream Montgomery Center project in October 2005. However, no significant damage or deposition appears to have resulted. It may be that the East Berkshire Bridge project is better suited to withstand high flow events due to lower channel sinuosity and more equilibrium conditions in terms of bedload transport and deposition. Extensive grading and planting have been done on the left bank upstream of the bridge.

Other than enhancing the growth of border ice in the immediate vicinity of the structures, ice formation in the project reach appears to be very similar to ice growth in unaltered natural sections of the Trout River. Figure 38 shows ice starting to form on the limbs of the in-stream structures on January 4, 2006 and Figure 39 shows a more complete ice cover on the project reach on January 31, 2008.

Figure 38. Trout River looking at the East Berkshire Bridge restoration project on 1/4/06.

It is likely that dynamic ice runs occur on the lower Trout River and that ice jams form a short distance below the project, upstream of its confluence with the Mississquoi River. Although conditions did not favor the occurrence of severe breakup ice jams during the 2005-2008 observation period, the project reach will probably experience significant ice events in the future.

Figure 39. Trout River East Berkshire Bridge restoration project on 1/31/08.

White River, Granville and Rochester, Rock Vanes, Cross Vanes. VT-ANR

These two small streambank stabilization projects are located in the upper White River watershed. At the upstream project, near the village of Granville, the river banks have been stabilized by a series of small vanes and four cross vanes made of quarried rock. The project appears to be performing as designed in terms of bank stabilization and deposition. The structures had withstood a mild mid-winter breakup ice run just prior to a 10 January 2006 field visit (Figure 40).

Figure 40. Cross vane stabilizing banks of the White River below Granville, VT following mid-winter breakup 1/10/06.

The downstream project, located above the village of Rochester, is similar, with vanes and cross vanes stabilizing the bank along the edge of a field (Figures 41 and 42). An earthen berm and a row of wooden posts have been constructed along the edge of the field with the likely purpose of preventing breakup ice from going out of bank during ice runs. The bank opposite the structures follows the edge of the valley and the structures appear to be resisting the natural tendency for the stream channel to cut the left bank and migrate into the field.

Figure 41. Vanes stabilizing bank of the White River above Rochester, VT. 1/10/06. Posts and berm to prevent ice from escaping into field of left.

Figure 42. Ice forming around rock vanes in the White River above Rochester, VT, 12/21/05.

7 Summary and Conclusions

A variety of streambank stabilization and river restoration structures were observed during the winters of 2005 to 2008. These structures, located on northern Vermont rivers, ranged from rock vanes to deflect flow outward and encourage sedimentation along banks; cross vanes and U-drops to concentrate flow towards the channel center, dig pools and reverse channel widening trends; and rock weirs to provide grade control and increase flow diversity. The projects were relatively new, ranging in age from one to ten years. In general, the structures achieved their intended river restoration and streambank stabilization goals, having experienced a minimum of damage from flood or ice events. One exception was the Trout River restoration project below Montgomery Center. Here, during a major open water flood in October 2005, bedload deposited in a restored meander caused a major channel avulsion back to pre-project flow paths.

No significant ice damage was observed at the projects during the four-winter monitoring period. This may be the result of relatively mild winter conditions with below-average ice production and frequent midwinter breakups that decreased winters-end ice volumes. Another mitigating factor was the absence of dynamic breakups and ice jams at the end of the winter seasons.

In general, the observations of ice type and geomorphologic setting of the projects fit the Bergeron et al, (2009) conceptual model, relating ice cover type to sediment links. A sediment link is a reach of river comprised of upper, middle and lower sections. The upper section which is steep, fast flowing, and coarse-bedded provides most of the sediment input to the link. The middle section is gravel-bedded and characterized by pool-riffle sequences, alternating bars and downstream fining of bed material. The lower section is deeper, slower flowing and sand-bedded.

In terms of ice type, the upper section will have open water leads promoting frazil ice growth and hydraulically thickened frazil ice accumulations, particularly along the channel sides. The middle section will host thick frazil ice accumulations on the riffles with border ice and juxtaposed frazil floes on the pools. Finally, the ice cover on the lower section will range from juxtaposed floes to border ice and thermally-grown

sheet ice. In general, the ice cover within a link becomes thicker and more competent as one moves downstream. The downstream trend towards thicker, stronger ice and decreasing slope and water velocity favor a downstream breakup progression. As a result, the chance of severe breakup ice jams and the potential for ice damage to a SS or RR structures also increases in the downstream direction. The most vulnerable area in terms of breakup ice jams is likely to be the transition zone from the middle to lower sections, as the ice supply becomes large in the face of diminishing ice conveyance capacity.

Most of the projects in this study lie in gravel-bedded, pool-riffle reaches in middle sections of sediment links. Little evidence was found of past destructive ice jams at these projects. Examples include the Warren Snow Making Ponds RR project on the Mad River and the Trout River RR project below Montgomery, which lie in depositional environments near the upstream ends of middle sections.

In this study, signs of past breakup ice jams increased in the downstream direction as the potential ice supply increased and valley slope decreased. Sites in transition zones from middle to lower sections of sediment links appeared to be the most vulnerable to damage from ice breakup. Examples include the recent Snowflake Farm and Gov. Chittenden vanes projects on the Winooski River which, due to their newness, have yet to experience severe ice events.

It is possible that the two rock vane projects on the Mad River, below Waitsfield, have already experienced significant ice damage in their ten years or so since construction. Unfortunately the lack of information on the original structure dimensions makes it hard to assess the extent of damage. The recently built structures on the lower Trout River, at East Berkshire, remain relatively untested as they have yet to experience a major ice event.

The two projects in the upper White River, at Granville and Rochester, showed little evidence of breakup ice damage, nor did the vanes and cross vanes on the upper Mad River near Warren, or the rock structures on the Trout River below Montgomery Center. These projects are on the order of ten years in age.

Based on the projects observed in this field study, the effects of the RR and SS structures on ice formation and the local river ice regime appear minimal. This may stem from the underlying design philosophy for modern RR and SS projects that attempts to re-create the natural channel characteristics of nearby “reference reaches”.

Low frequency-high magnitude events, involving either open water or ice, pose the greatest risk to RR and SS projects. It appears that the passage of time between construction and the occurrence of the large event favors their survival. The projects are probably most vulnerable to flood or ice damage immediately following construction before sediment has deposited or soil strengthening riparian vegetation has taken hold. The farther along this sedimentation and plant establishment is at the time of the event, the better the chances are for the project’s survival.

Due to the lack of any severe ice events during the 2005-2008 period, it would be worthwhile to continue monitoring of selected projects, particularly those on the lower Winooski (Snowflake Farm and Gov. Chittenden vanes) and Trout Rivers (East Berkshire Bridge). The potential for severe breakup ice events appears to be the greatest at these projects. Two visits per year, one in the late fall (after any open water flooding and before ice formation) and one in the early spring (after ice breakup) are recommended.

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14. ABSTRACT

Modern river restoration and streambank stabilization designs are taking more natural approaches. Examples include vanes and weirs constructed of rocks or logs that encourage bank sedimentation and direct flow toward the channel center, also rock riffles and weirs to control grade. Successful projects help control bed and bank erosion, re-connect floodplains, increase flow diversity and improve habitat for fish and wildlife. To date, the design of these increasingly popular structures has been largely empirical and little is known about their performance on rivers with ice. In addition to the uncertainty of the structures' survival in ice, little is known about their effect on river ice processes. Recent research at CRREL has developed ice-related design guidance for these structures. This effort included performance monitoring of streambank stabilization and river restoration projects on ice-affected rivers in northern Vermont over the three year period from 2005 to 2008. Results and findings are presented in this report.

15. SUBJECT TERMS

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	cross vanes	freezeup

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